RADAR-OBSERVED CHARACTERISTICS OF PRECIPITATION IN THE TROPICAL HIGH ANDES OF SOUTHERN PERU AND BOLIVIA

A Thesis
by
JASON LEE ENDRIES

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Abstract

RADAR-OBSERVED CHARACTERISTICS OF PRECIPITATION IN THE TROPICAL HIGH ANDES OF SOUTHERN PERU AND BOLIVIA

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This study investigates precipitation delivery using the first detailed radar measurements of the vertical structure of precipitation obtained in the tropical Andes of southern Peru and Bolivia. A vertically pointing 24.1 GHz Micro Rain Radar in Cusco, Peru (3,350 m asl, August 2014-February 2015) and La Paz, Bolivia (3,440 m asl, October 2015-February 2017) provided continuous 1-min profiles of reflectivity and Doppler velocity during the respective time periods. These data enabled the determination of precipitation timing and melting layer heights and the identification of convective and stratiform precipitation features. Thermodynamic profiles from rawinsonde releases, hourly observations of various meteorological variables, and backward air trajectories from the NOAA HYSPLIT model provided additional insight into the characteristics of these precipitation events. The vertically-pointing radar time-height data reveal a bimodal diurnal cycle in precipitation with cellular convection predominant in the afternoon and stratiform precipitation predominant overnight. Backward air trajectories for two stratiform case studies indicate that low-level flow originated in the Amazon basin three days prior to the events.

Median melting layer heights were above the altitude of nearby glacier termini (~5,000 m) approximately 17% of the time in Cusco and 30% of the time in La Paz, indicating that some precipitation is falling as rain rather than snow on nearby glacier surfaces. Higher melting layer heights in La Paz during the 2015-16 El Niño (47% above 5,000 m) suggest that understanding precipitation processes is critical for understanding future changes in glacier behavior and water resources in the region.

Acknowledgments

The completion of my Master’s degree did not start when I moved to Boone to attend Appalachian State, but rather began years ago when I became fascinated with the weather. Thanks to my parents Mark and Bonnie Endries who fostered my childhood curiosity, this fascination turned into a passion. Their support, even with all of the time spent on the Weather Channel, the money spent on meteorology toys, and the suspense of me playing outside during Hurricane Isabel, led me to pursue meteorology in higher education.

I attended North Carolina State University (NCSU) for a B.S. in Meteorology, where I not only matured as a person but was also given the opportunity to grow as an academic. Dr. Sandra Yuter, my advisor at NCSU and current committee member, was vital to making my time at the university so much more than just a degree-seeking experience. She hired me as an undergraduate researcher during my sophomore year, gave me a Matlab how-to book, and nurtured me along the way. Not only did I gain invaluable investigative and programming experience in her research group, she also opened my eyes to the possibility of getting my master’s degree in a geography program.

This is where Dr. Baker Perry entered, who saw potential in me and guided me through the tumultuous path of graduate school with ease. Since I started at Appalachian in the fall of 2015, Dr. Perry has funded four separate trips to the Andes for me during which I practiced my Spanish, camped on glaciers, collected data, and led field operations. He has thoughtfully and critically guided my research through every automated graphing script written, every presentation given, and every draft of my thesis. My graduate degree has been a complete immersion into observational research that I am now more familiar with than next week's forecast. Apart from the academics, Baker has also opened up his family's home to me for dinners, gone on runs with me, and provided rides to the airport when the snow was just too deep.

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Finally, I would like to gratefully acknowledge all of my coauthors for their scientific expertise, data support, and critical eyes, and Fabricio Avila for providing technical support for instrumentation in Bolivia. NOAA's Air Resources Laboratory is also acknowledged for the use of the HYSPLIT model. Funding supporting this research was provided by the

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Foreword

The main body of this thesis is formatted to the guidelines for manuscript submission to the *Journal of Applied Meteorology and Climatology*, an official journal of the American Meteorological Society.

Introduction

In the tropical high Andes of southern Peru and Bolivia, glaciers are shrinking and have been doing so for several decades (Francou et al. 2003; Rabatel et al. 2013; Salzmann et al. 2013; Hanshaw and Brookhagen 2014). While climate change is still a distant and hypothetical notion in many regions of the world, the delicate mountain regions in this part of the world are already seeing impacts. Disappearing glaciers threaten local fresh water resources, hydropower productivity, and the availability of paleoclimate records (Vimeux et al. 2008). Higher temperatures (Rabatel et al. 2013), rising humidity (Salzmann et al. 2013), and changing precipitation patterns (Perry et al. 2014, 2017) are all factors contributing to increased glacier ablation. Unfortunately, current precipitation patterns of the tropical high Andes are not well understood (Francou et al. 2003; Perry et al. 2014). It is therefore difficult to evaluate future changes in the impact of precipitation events on glaciers in the area.

Large scale precipitation delivery mechanisms have been investigated in many previous studies (Garreaud 1999; Lenters and Cook 1999; Vuille 1999; Garreaud 2000; Garreaud et al. 2003; Falvey and Garreaud 2005; Krois et al. 2013). Generally, moisture availability in the central Andes is controlled by flow in the middle-upper troposphere, with easterly flow drawing moisture from the Amazon basin during the wet season (December-February) and westerly flow preventing moisture advection during the dry season (May-October) (Garreaud et al. 2003; Krois et al. 2013). Trough passages can enhance moisture advection from the Amazon basin into the central Andes (Garreaud 1999; Lenters and Cook 1999). El Niño has also been shown to affect moisture availability in the region by strengthening westerlies, reducing humidity, and increasing temperatures (Vuille 1999). However, analyses considering the spatial variability of precipitation timing, amount, and structure in the central Andes are lacking. This research presents the first high altitude vertically pointing radar dataset collected in the central Andes of southern Peru and Bolivia, and contributes an analysis of the vertical structure and melting layer heights of the precipitation.

Data that I utilized for this study, including 1-minute vertically pointing radar observations and surface meteorological variables, were collected between 2014-17 in Cusco, Peru and La Paz, Bolivia. Additionally, I co-led two field campaigns to launch rawinsondes and collect vertical temperature and winds profiles during precipitation events in La Paz. To prepare the data, I took processed the vertically pointing radar data using a procedure outlined in Maahn and Kollias (2012), wrote algorithms to detect melting layer heights and event durations, and quality controlled the results using the rawinsonde data and visual analysis. In total, 682 days, consisting of 539 precipitation events and 3197 precipitation hours, were captured. I used an exploratory approach in this study due to the size of the data and a lack of radar analyses or investigations of precipitation structure in the central Andes. Histograms that I created revealed a diurnal pattern of precipitation, and scatter density plots uncovered both a diurnal and seasonal cycle of melting layer heights and event durations. An in-depth analysis of 3 case studies uncovered the melting layer heights associated with stratiform and convective precipitation as well as the direction from which moisture traveled that contributed to the precipitation events.

The results from this study will help to complete our conceptual understanding of precipitation processes and patterns in the central Andes. A bimodal precipitation pattern in the region, with one nighttime and one afternoon peak, is confirmed using high temporal resolution radar data. In particular, the study reveals intricacies in the vertical structure of precipitation in the high tropical Andes not previously observed. The character of events ranged from high intensity convective, to long duration nighttime stratiform, to mixed stratiform and convective precipitation. This research also opens areas of future work, including the relationship between El Niño and the altitude of the melting layer, and the mechanisms behind the formation of stratiform precipitation in the region.

Radar-Observed Characteristics of Precipitation in the Tropical High Andes of Southern Peru and Bolivia

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Abstract

This study investigates the meteorological processes associated with precipitation delivery using the first detailed radar measurements of the vertical structure of precipitation obtained in the tropical Andes of southern Peru and Bolivia. A vertically pointing 24.1 GHz Micro Rain Radar in Cusco, Peru (3,350 m asl, August 2014-February 2015) and La Paz, Bolivia (3,440 m asl, October 2015-February 2017) provided continuous 1-min profiles of reflectivity and Doppler velocity during the respective time periods. These data enabled the determination of precipitation timing and melting layer heights (MLHs) and the identification of convective and stratiform precipitation features. Thermodynamic profiles from rawinsonde releases, hourly observations of various meteorological variables, and backward air trajectories from the NOAA HYSPLIT model provided additional insight into the characteristics of these precipitation events. The vertically-pointing radar time-height data reveal a bimodal diurnal cycle in precipitation with cellular convection predominant in the afternoon and stratiform precipitation predominant overnight. Backward air trajectories for two stratiform case studies indicated that low-level flow originated in the Amazon basin three days prior to the events. Median melting layer heights were above the altitude of nearby glacier termini (~5,000 m) approximately 17% of the time in Cusco and 30% of the time in La Paz, indicating that some precipitation is falling as rain rather than snow on nearby glacier surfaces. Higher melting layer heights in La Paz during the 2015-16 El Niño (47% above 5,000 m) suggest that understanding precipitation processes is critical for understanding future changes in glacier behavior and water resources in the region.

1. Introduction

The glaciers of the tropical Andes of southern Peru and Bolivia have experienced substantial impacts due to climate change and variability, with extensive retreat and negative mass balance since 1980 including the disappearance of many small glaciers (Francou et al. 2003; Rabatel et al. 2013; Salzmann et al. 2013; Hanshaw and Brookhagen 2014). Reductions in the duration or frequency of precipitation, increases in the altitude of the melting layer height (MLH; i.e., the snow level), and delays to the start of the wet season are resulting in the disappearance of an important freshwater source and also threatening thousands of years of paleoclimate records (Rabatel et al. 2013; Salzmann et al. 2013). However, a poor understanding of the precipitation processes and patterns that control the behavior of these glaciers limits both the ability to adequately prepare for future climate change and to reconstruct historical climates from ice cores obtained from this region (Vimeux et al. 2008; Kellerhals et al. 2010).

More than 60% of all tropical glaciers are found in the Andes between 12-16° S, in southern Peru and western Bolivia (Fig. 1) (Rabatel et al. 2013). It is now well established that the equilibrium line altitude (ELA) on these glaciers, the altitude where mass is neither gained nor lost, has risen to as high as 5400 m above sea level (m asl; this is the unit of all altitudes in this study), resulting in decreasing glacial area and negative mass balance (Rabatel et al. 2013; Hanshaw and Bookhagen 2014). The melting layer height during precipitation plays an important role in the determination of the ELA by controlling albedo, an important control of ablation, at the glacier surface (Fig. 2) (Francou et al. 2003; Salzmann et al. 2013; Hanshaw and Bookhagen 2014). Fresh, bright snow will sustain high albedo, whereas rain can promote melting, significantly reduce albedo, and expose older, darker glacier surfaces. Rising melting layer heights are therefore a major contributing factor to the increased ablation of snow and ice, and in some cases the complete disappearance of glaciers in recent decades (Francou et al. 2003; Salzmann et al. 2013). However, there is a limited understanding of the mechanisms that control vertical precipitation structure, as well as the character and timing of precipitation events in the tropical Andes (Francou et al. 2003; Perry et al. 2014). Timing, referring to nighttime or daytime, and character, referring to long duration stratiform or short and intense convection, of precipitation play an important role in determining the precipitation accumulation that a single event delivers to the glacier surface. A better insight into the complexities of these meteorological processes can help Peru and Bolivia to manage their water resources in a warming climate and help the wider scientific community interpret the records of past climates that are preserved in the ice.

Using observational data from 539 precipitation events captured by a high-elevation vertically-pointing radar during deployments at two locations, this study addresses two questions: 1) How does the timing and vertical structure of precipitation events vary based on the regional atmospheric conditions and local geographic characteristics of Cusco, Peru and La Paz, Bolivia? and 2) What are the associated geographic and temporal distributions of melting layer heights? The findings developed from the analysis help to inform the conceptual model of precipitation delivery in the region as well as provide insight into the precipitation-glacier interactions in a changing climate.

Section 2 will present a synthesis of the current understanding of precipitation climatology in the tropical Andes, as well as past applications of using vertically pointing radar observations to detect the melting layer and character of precipitation. Section 3 will provide a summary of the results and an analysis of three case studies that are characteristic of precipitation events observed in the dataset. In Section 4, the results and their implication for our understanding of precipitation patterns in the tropical high Andes will be discussed. Finally, Section 5 will summarize the findings and present some applications of the work.

2. Background and Literature Synthesis

a. Precipitation climatology in the tropical Andes

The annual climatology of the Andean regions of Peru and Bolivia is characterized by a distinct wet season that occurs during the austral summer from December to February. The existence of a wet season relies on easterly winds in the middle-upper troposphere that persist throughout most of the period (Krois et al. 2013), while westerly winds persist from May to October during the dry season (Garreaud et al. 2003). The wet season is also characterized by a southward (poleward) displacement and intensification of the Bolivian High (Vuille 1999), an upper-tropospheric, closed counterclockwise circulation that is centered over Bolivia in the austral summer.

The upper-level easterly winds during the wet season are associated with a southward (poleward) expansion of the belt of equatorial easterlies (Garreaud et al. 2003). These easterlies frequently act to transport abundant lower tropospheric Amazonian moisture over the South American Altiplano during the wet season and other periods of anomalous easterly zonal winds (Garreaud et al. 2003). Most of the moisture for the events observed in the central Andes originates in the Amazon. In the Cordillera Vilcanota for example, 95% of the events in Cusco, Peru occurred with 72-hour moisture trajectories inflowing from the Amazon basin (Perry et al. 2014). Data from meteorological stations across the Altiplano reveal that this influx of moisture occurs across the entirety of the Altiplano and affects the meteorology of the whole region as a result (Garreaud 2000). Precipitation typically occurs in alternating periods of wet and dry episodes of about a week, corresponding to fluctuations in the zonal flow (Garreaud et al. 2003; Falvey and Garreaud 2005). Moist periods seem to frequently result in active convection in the Altiplano (Garreaud et al. 2003).

The early stages of trough passages across South America, corresponding to a southward (equatorward) displacement of the Bolivian High, result in easterly and northerly winds which aid in the advection of air with a high equivalent potential temperature from the Amazon over the Andes and into the Altiplano (Garreaud 1999; Lenters and Cook 1999). Similar to the mechanisms that control the wet season, this draws air with elevated levels of specific humidity into the inter-Andean region, which favors convection and increases the chances for precipitation across the area. At the Quelccaya Ice Cap, more than 70% of wet season snow accumulation between 2003-14 correlates with migratory trough passages across southern South America with great equatorward reach (Hurley et al. 2015). These cold frontal passages, identified as one of the primary causes of snowfall at 4500 m in northern Chile (Vuille and Ammann 1997), may also play a role in delivering precipitation to the tropical Andes (Hurley et al. 2015).

The later stages of trough passages and a northward (equatorward) displacement of the Bolivian High produce westerly winds that carry drier air from the Pacific. Precipitation is inhibited in the Altiplano during these episodes, analogous to the dry season, however widespread nocturnal convection and morning stratiform precipitation over the northeastern foothills of the central Andes can occur (Romatschke and Houze 2010). The displacement of the Bolivian high is not necessarily the cause of higher precipitation in the Altiplano but rather an upper-level response to low-level mechanisms such as the anomalous release of latent heat during rainy periods (Lenters and Cook 1999). However, the placement of the high pressure feature may still be a useful predictor of precipitation in the study area.

On seasonal to annual time scales, precipitation in the tropical high Andes is also regulated by teleconnections to large-scale phenomena such as ENSO. Vuille (1999) found that during El Niño austral summers, westerlies and northerlies increase, specific humidity is reduced, and the troposphere is anomalously warm. Stronger westerlies may inhibit the easterly penetration of moist air from interior South America into the Altiplano (Vuille 1999). During El Niño, the Bolivian High is weakened and displaced to the north, and precipitation in the Altiplano is reduced. Vuille (1999) found that conditions are overall opposite during La Niña austral summers. However, the complex topography of the Andes makes the impacts of ENSO on specific localities varied. El Niño conditions result in less precipitation and higher air temperatures in the region of the Chacaltaya and Zongo glaciers in the Cordillera Real, Bolivia, leading to a loss of glacier mass (Wagnon et al. 2001; Francou et al. 2003). On the other hand, in Cusco and the Cordillera Vilcanota in south central Peru El Niño was found to lead to positive precipitation anomalies, while La Niña produced negative anomalies (Perry et al. 2014).

At the mesoscale, several studies indicate a diurnal pattern of precipitation occurrence across the central and northern Andes, with peaks in the overnight hours and afternoon (Bendix et al. 2006, 2009; Romatschke and Houze 2013; Mohr et al. 2014; Perry et al. 2014). Some studies reveal that the afternoon maximum can be attributed to convection due to surface heating (Bendix et al. 2006, 2009; Krois et al. 2013; Perry et al. 2014). Data from these studies, including GOES-E satellite imagery and backwards air trajectories, provide evidence that the precipitation that results in the regional nighttime peak originates from convection over the adjacent Amazon basin to the north and east (Bendix et al. 2009; Perry et al. 2014). Tropical Rainfall Measuring Mission (TRMM) (Kummerow et al. 1998) satellite data show that large area precipitation echoes peak in occurrence during the late night to early morning period across the Amazon basin (Romatschke and Houze 2013). Romatschke and Houze (2010) attribute the detection of these broad echoes, which typically occur in the hours after wide convective cores develop, to be evidence that MCSs are the source of the nighttime precipitation in the region.

b. Precipitation signatures in MRR data

Vertically pointing radars have been used widely to gather information on the vertical structure of precipitation events (Cha et al. 2007; Bendix et al. 2006; Lundquist et al. 2008; Das and Maitra 2011; Minder et al. 2015). These data can be useful when determining the character, or the stratiform and convective nature, of precipitation events. Stratiform precipitation has a layered appearance with a relatively narrow distribution of reflectivity values at each altitude and most vertical velocities less than 1 m s^{-1} (Houze 1997). On the other hand, convective precipitation has a much broader distribution of reflectivity and velocities with magnitudes that can exceed 10 m s^{-1} (Houze 1997).

In the Andes, very few studies have utilized vertically pointing radar data to analyze precipitation structure. One such study uses Micro Rain Radar (MRR) data from southern Ecuador to demonstrate that precipitation character in the region can be inferred using rain rates (Bendix et al. 2006). The study loosely corroborated average disdrometer values from Tokay et al. (1999) of 1.86 mm hr^{-1} during stratiform precipitation and 10.5 mm hr^{-1} during convective precipitation. Most of the events captured were stratiform in character, although the authors note the importance of embedded convection as an important feature of precipitation delivery in the Andes of southern Ecuador.

The melting layer height has been identified using vertically pointing radars in a variety of studies (White et al. 2002; Lundquist et al. 2008; Das and Maitra 2011; Minder and Kingsmill 2012). Das and Maitra (2011), for example, identified the top of the melting layer as the altitude where the maximum negative gradient in rain rate occurred. These results, when compared to vertical temperature profiles of rawinsonde data, proved to be remarkably accurate. The methods outlined in White et al. (2002) were utilized by Minder and Kingsmill (2012) and Lundquist et al. (2008) to derive the elevation of the brightband using Doppler vertical velocity and range-corrected signal-to-noise ratio. Moving up within the profile, the altitude where velocities began to decrease with height concurrently with increasing reflectivities indicated the location of the brightband peak. Used in conjunction with rawinsonde and other meteorological data, Lundquist et al. (2008) evaluated the efficacy of remotely-sensed brightband levels at estimating the actual snow line on the windward mountain slopes in the Sierra Nevada. Even though the brightband heights were detected up to 300 km away from the mountain, they coincided well with the altitude at which the melting layer height intersected the surface. These studies suggest that vertically pointing radars can be used to estimate the altitude of the melting layer, and thus the 0°C level, with reasonable accuracy. Generally, the top of the brightband provides an accurate estimate of the level of the 0°C isotherm, as most snowflakes melt by the time the ambient temperature reaches 0.5°C (Yuter et al. 2006). Although snow in the Bolivian Andes has been detected in temperatures as high as +1.8°C, the percentage of snow detected across all precipitation samples did not rise above 50% until the 0-0.5°C temperature range (L’hôte et al. 2005).

3. Data and Methods

A wide variety of data were collected for this study across the study area of southern Peru and western Bolivia (Table 1). From September 2014 to February 2015, a vertically pointing 24.1 GHz MRR (Peters et al. 2002) collected data every minute for 169 days in Cusco, Peru (13.55° S, 71.98° W; 3350 m). The MRR was moved to La Paz, Bolivia (16.54° S, 68.07° W; 3440 m) to collect data for 513 days, from October 2015 to February 2017. These data were continuous and therefore sampled both the wet and dry seasons. In order to remove noise and improve data quality and sensitivity for snow observations, these data were post-processed using the technique outlined in Maahn and Kollias (2012). A simple algorithm was also used to develop statistics describing the timing and duration of precipitation events in the MRR datasets at each location. Event durations were defined as the length that echoes were detected in the bottom bin of the vertical radar profile with no longer than 3 hour breaks. A new event was defined after 3 hours passed with no echoes in the bottom bin. We assessed these quality-controlled MRR data to examine the vertical structure and duration of precipitation, and determine if a precipitation bearing system was stratiform or convective in character. Long duration events with horizontally layered reflectivity values implied stratiform precipitation. Short duration events with more homogenous vertical reflectivity profiles implied convective precipitation (Houze 1997).

The MRR data was also used to identify the melting layer height, the level at which frozen hydrometeors begin to melt after falling through the 0°C isotherm into above-freezing temperatures. If the vertical spatial resolution is sufficient, the melting layer height will appear in a vertical reflectivity profile of stratiform precipitation as a brightband, a layer of increased reflectivity followed by an increase in Doppler velocity (Houze 1997). As a snow crystal falls through the atmosphere from below to above freezing conditions, water droplets form on the flake. This increases the radar-detected reflectivity due to the higher dialectric constant of water than of ice. Once melting is complete, the denser rain drop will fall at a higher velocity than the snowflakes above. Using these principles, highlighted by Austin and Bernis (1950), we developed an algorithm to identify the top of the melting layer as the most negative gradient in reflectivity and the bottom of the melting layer as the most negative gradient in Doppler velocity in the profile. The melting layer height was then computed every minute as the bottom of the melting layer during that minute plus the average melting layer thickness (top minus bottom) during the respective hour of the storm. Melting layer heights were discarded if the algorithm produced values: 1) outside of one standard deviation of the mean of the hour in which it lies, 2) above 6000 m in altitude, which is considered implausible under current tropospheric conditions, or 3) existing during virga, defined as occurring when no precipitation is detected below 4000 m. The final quality controlled dataset is comprised of the median hourly melting layer height derived from these one-minute derived values.

Surface METAR observations from the Cusco International Airport (SPZO) and El Alto International Airport (SLLP), as well as data from a meteorological station collocated with the MRR in Cota Cota, La Paz, were collected for the MRR observation periods at each location. These helped provide a context for the conditions under which storms occurred. To verify the melting layer height values and confirm a simple atmospheric profile, vertical profiles of temperature were collected from 5 rawinsonde launches in early March 2016 and 10 launches in early January 2017 from the site of the La Paz MRR. The launches were conducted during precipitation events and revealed a consistently simple vertical temperature profile without significant inversions (Fig. 3). All of the 15 recorded profiles crossed 0°C only once, an average of 183 m higher than the temporally closest derived melting layer height value during the storm. This is similar to findings by Austin and Bernis (1950), and is likely attributable to a mean lapse rate of 5.98°C km^{-1} throughout the melting layer and the time it takes for the frozen precipitation to respond to the ambient temperature.

In order to provide a context for the synoptic conditions during precipitation events in the study area, ERA-Interim data, a set of global atmospheric reanalysis data produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Dee et al. 2011), were employed. Point data were extracted to evaluate 500 and 250 mb meteorological variables over the location of the MRR during three case studies. Additionally, National Oceanic and Atmospheric Administration (NOAA) Global Data Assimilation System (GDAS) 0.5° data were used to create backward trajectories with the NOAA Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) Model for case studies in La Paz and Cusco. Air parcels were tracked from 4000 m during the hour during which the storm began to 72 hours prior. The HYSPLIT Model may not accurately represent the sources of moisture during periods of weak flow, and the high terrain and sharp relief of the study area might impact its performance. However, these trajectories allowed for a broad analysis of the predominant directions from which air parcels originated that contributed moisture to the case studies in Cusco and La Paz.

4. Results

a. Overview

The MRR data from both Cusco and La Paz revealed distinct patterns in the timing and duration of precipitation, as well as the melting layer height during precipitation, at each location. A summary of precipitation occurrence (Fig. 4), when there was any echo detected by the MRR in the vertical profile, shows that both locations exhibited one maximum of precipitation frequency in the afternoon (17-20 UTC) and a second before local midnight (0-4 UTC) in all seasons and years. Despite a similar pattern, there was greater diurnal variability in the data from Cusco than from La Paz. The Cusco data also revealed later and shorter maxima in precipitation frequency. The earliest afternoon hour that most frequently contained precipitation at Cusco occurred at 19 UTC, and the earliest nighttime hour occurred at 02 UTC. However, the afternoon peak in the La Paz data occurred as early as 17 UTC, and the earliest nighttime peak occurred at 00 UC.

Throughout the entire dataset, median event duration was longest in Cusco around local noon between 13-18 UTC, but around local midnight between 01-06 UTC in La Paz (Table 2). The longest events, with durations in the top quartile of the entire dataset, also began earlier in La Paz (overnight, 01-06 UTC) as compared to Cusco (evening, 19-00 UTC). The median of event durations in the top quartile that occurred during these respective periods was 9.4 hr in Cusco and 8.0 hr in La Paz (Table 2). Meanwhile, the median of event durations in the top quartile in both Cusco and La Paz were the shortest in the early morning between 07-12 UTC (Table 2). These events lasted aa median of only 4.0 hr in Cusco and 4.7 hr La Paz.

In addition to a diurnal pattern, a seasonal pattern of precipitation frequency is also evident in the MRR data. As expected, there were more events that occurred in the middle of the wet season (DJF) than in the drier season of austral spring (SON) (Fig. 5). This difference is highest during the 2015-16 season in La Paz, when only 48 events were recorded in SON while 98 events were recorded in DJF. Apart from JJA 2016 in La Paz (which has a relatively small sample size), DJF featured the longest events in all seasons in the dataset, particularly in Cusco during DJF 2014-15 (Table 3; Fig. 5b, 5d, 5f). The median event durations in Cusco during that season, and in La Paz during DJF 2015-16 and 2016-17, were 3.3, 1.8, and 2.0 hr respectively. Minimum event duration occurred in Cusco during SON 2014, and in La Paz during austral fall (MAM) 2016 and SON 2016. The top quartile of event durations follow the same seasonal pattern. The longest events (with event durations in the top quartile) in both Cusco and La Paz occurred during DJF 2014-15 and DJF 2016-17 respectively, and reached median values of 8.8 and 6.7 hr (Fig. 5; Table 3). During SON 2014, the longest events in Cusco lasted a median of only 4.1 hr. The longest events in La Paz during MAM 2016 also lasted a median of 4.1 hr.

Analysis of the derived median melting layer height data uncovered clear differences between the distribution of the heights over La Paz and over Cusco. In the La Paz dataset, there was both a wider variability in median melting layer height values and higher melting layer height values overall (Table 4). Quantitatively, melting layer heights were at or above 5000 m 30% of the time in La Paz as opposed to 17% of the time in Cusco. Median melting layer height values across all the 539 recorded events were higher in La Paz (347 events) than in Cusco (192 events) by 45 m, and maximum values were 63 m higher in La Paz. The range in melting layer heights was also larger in La Paz, with a standard deviation that was

44 m greater than Cusco. The top quartile of stratiform precipitation events from both the Cusco and La Paz datasets were identified using storm total precipitation accumulation as measured by SPZO and the Cota Cota, La Paz station and used for further analysis. During these events with high storm total accumulation, the mean and median melting layer height was lower than for the entire population in Cusco, but higher in La Paz (Table 4).

There were also similarities in the diurnal and seasonal patterns of the melting layer height in the two locations (Fig. 6; Table 5). The highest median melting layer height values over both Cusco and La Paz occurred during the afternoon (19-00 UTC), while the lowest occurred in the early morning (07-12 UTC) in Cusco and overnight (01-06 UTC) in La Paz. melting layer height values were frequently highest in the afternoon and evening (15-00 UTC) and lowest in the early- to mid-morning (06-15 UTC) (Fig. 6). The more pronounced diurnal variability of melting layer heights in the Cusco dataset was notable (Table 5), particularly in DJF 2014-15 (Fig. 6b). A coinciding seasonal pattern in melting layer height values between the two locations also existed. Lowest median melting layer heights occurred during JJA 2016 when median values only reached 4401 m in La Paz (Table 6). During DJF however, median melting layer height values in 2014-15, 2015-16, and 2016-17 respectively reached 4850 m in Cusco, with even higher values of 5064 and 4890 m in La Paz (Table 6).

b. Case Studies

1) Cusco, 15 January 2015 – strong convective precipitation

On 15 January 2015, a convective precipitation event began at 1730 UTC (1230 PET) at the location of the MRR in Cusco, Peru and lasted approximately 2 hours until 1930 UTC (Fig. 7; Table 7). The convective and localized nature of the event is revealed by the meteorological variables recorded at SPZO (1.3 km from the MRR), with a mean temperature of 16.8°C throughout the event and only 0.8 mm of accumulated precipitation. The convective nature of the precipitation is also evident in the MRR profile in Fig. 7, with attenuated reflectivity values above 30 dBZ higher than 7100 m just after 18 UTC. Strong vertical motions removed any melting layer height signal from the MRR data. At 1800 UTC, before the heaviest precipitation began, the ERA-Interim Reanalysis data show that winds at 500 hPa (approximately 5890 m) were out of the southwest at 4.8 m s^{-1} (Table 8). At 250 hPa, the winds shifted to the northwest at 8.0 m s^{-1}. The HYSPLIT backwards air trajectory beginning at 4000 m (Fig. 7c) suggests that the moisture for the convective event originated to the north in the area of the Amazon basin almost three days prior. This northerly to southwesterly to northwesterly flow suggests winds were veering both clockwise and anticlockwaise with height. A map of TRMM-detected regional precipitation rate from three hours before to 3 hours after the event (Fig. 7c) shows that the focus of precipitation was to the north in the foothills, with 0-22 mm of precipitation in the area around Cusco.

2) Cusco, 08 October 2014 – stratiform precipitation

A long duration stratiform precipitation event impacted Cusco on 08 October 2014, beginning at approximately 0030 UTC (1930 PET) and persisting until 0630 UTC (0130 PET) (Fig. 8; Table 7). The mean surface temperature observed at SPZO during this event was 9.8°C. Storm accumulated precipitation from this event was in the top quartile of the Cusco dataset, totaling 16.6 mm. The melting layer height during this event is easily identifiable and ranged between 4729, 4915, and 4304 m at the beginning, middle, and end of the precipitation respectively (Fig. 8a and 8b). Winds during this event were veering clockwise with height, with a northeasterly low level trajectory (Fig. 8c) and ERA-Interim winds at 0600 UTC from the southeast at 5.9 m s^{-1} at 500 hPa and from the southwest at 8.0 m s^{-1} at 250 hPa (Table 8). The 500 hPa geopotential height was slightly lower (5883 m) than during the convective event. Moisture contributing to this event originated more than two days before to the east in the Amazon basin (Fig. 8c). Compared to the convective case, this long lasting stratiform case covered a much larger area per the TRMM precipitation map (Fig. 8c). Precipitation occurred in an area from southeast to northwest of Cusco between 2 hours before to 4 hours after the detected precipitation in Cusco.

3) La Paz, 25 February 2016 – heavy stratiform precipitation

A stratiform precipitation event in the top quartile of the La Paz dataset began on 24 February and lasted for 42 hours under the definition using 3-hr breaks. For this analysis, the intermittent precipitation shown in Fig. 9 between 1400 UTC (1000 BOT) 25 February to just after 1400 (1000 BOT) UTC 26 February will be the focus. melting layer heights were almost constant throughout, beginning at an altitude of 5050 m and rising slightly to 5090 m by the end of the event (Fig. 9a and 9b). The median melting layer height reached 5129 m (Table 7). These high melting layer height values may have been influenced by the high tropospheric temperatures, with mean surface temperatures of 12.1°C throughout the precipitation as measured by a meteorological station collocated with the MRR. The same station recorded a total of 24.2 mm of accumulated precipitation. During the event at 0000 UTC, winds at 500 hPa were from the southwest at 6.8 m s^{-1} and from the southwest at 2.0 m s^{-1} at 250 hPa (Table 8). The backwards air trajectory suggests winds veered anticlockwise with height, with air parcels moving northeasterly towards La Paz and originating from the region of the Amazon to the east three days prior (Fig. 9c). Precipitation paralleled the eastern side of the Andes throughout the event, with a maximum in accumulated precipitation in central Bolivia, in the foothills to the east of La Paz (Fig. 9c).

5. Discussion

The clear pattern observed in the datasets from both La Paz and Cusco of daytime and nighttime precipitation maxima (Fig. 4), and daytime convective and nighttime stratiform vertical precipitation structure, can be largely attributed to strong diurnal fluctuations in surface temperature that the tropical Andes experience. melting layer heights are highest in the afternoon (15-00 UTC) (Fig. 6; Table 5) and associated with a deep, well-mixed planetary boundary layer following daytime surface heating. Long duration events typically begin during the afternoon (19-00 UTC) and overnight (01-06 UTC) periods (Fig. 5; Table 2), as surface temperatures decrease, convection weakens, and vertical air motions slow (Houze 1997). The post-midnight through sunrise hours (07-12 UTC) are characterized by low melting layer heights as surface temperatures are at nocturnal minima and precipitation is predominantly stratiform. The early morning is also characterized by the beginning of the shortest duration events. Finally, a lull in precipitation occurs before to just after local noon (13-18 UTC) (Fig. 4) as surface temperatures to rise with solar heating. This diurnal cycle was also observed in Cusco by Perry et al. (2014) using hourly precipitation data from SPZO, with one maxima in the afternoon and one close to local midnight.

The geography of the study area, particularly differences in elevation and proximity to the Amazon basin, may explain some of the variability observed in the timing and vertical structure precipitation. At an altitude of 3440 m and encircled by a 20 km radius mean elevation of 4004 m, La Paz experiences a higher percentage of precipitation in the afternoon than does Cusco, which lies at 3350 m and has a 20 km mean elevation of 3793 m. Between the hours of 18-20 UTC, the La Paz dataset contains 3% more of the total precipitation hours than does the Cusco dataset (Fig. 4). This is similar to a finding in Perry et al. (2017) whereby the meteorological stations at high elevations (e.g., Quelccaya, Murmurani Alto, and Chacaltaya) experience more precipitation in the afternoon than do stations at lower elevations. A possible physical mechanism behind these observations may be the *Massenerhebung* (mountain mass elevation) effect, whereby precipitation frequency and associated biological diversity on higher mountains occurs at higher elevations than the same conditions on lower mountains (Flenley 1995). The extremely large mountains close to La Paz (Illimani, 6438 m; Huayna Potosi, 6088 m; Mururata, 5871 m) are likely instrumental in driving daytime convection in the area. Through the mountain mass elevation effect, these mountains may raise the altitude where afternoon convective precipitation occurs, thereby increasing the amount of afternoon precipitation in La Paz.

Distance from the Amazon basin, the major proximal source of moisture for the central Andes (Garreaud 1999, 2000; Garreaud et al. 2003; Perry et al. 2014), may also influence afternoon precipitation patterns. Our dataset shows that Cusco experienced a peak in afternoon precipitation at 19 UTC in DJF 2014-15, two hours after the DJF 2016-17 afternoon peak in La Paz (Fig. 4). The proximity of La Paz to the Amazon basin, approximately 28 km from the upper forest boundary (as measured from satellite imagery), as opposed to Cusco (~56 km) may allow for earlier convective release due to the closer availability of Amazonian moisture and instability.

Differences in the behavior of precipitation may also be explained by a difference in atmospheric baseline states between the two datasets, particularly with regard to ENSO phase. The 2015-16 MRR data from La Paz were collected during a strong El Niño, with a September 2015-February 2016 mean Multivariate ENSO Index (MEI) (Wolter and Timlin 1993) value of +2.2. Anomalously higher tropospheric temperatures prevailed across the tropical Andes, following the recognized pattern of strong El Niño events (Vuille 1999; Wagnon et al. 2001). However, the 2014-15 Cusco and 2016-17 La Paz datasets were collected during relatively neutral phases of ENSO (2014-15, mean MEI = +0.5; 2016-17, mean MEI = -0.2). Daily maximum surface temperatures recorded at SPZO were 0.9°C greater on average from 01 November 2015-31 March 2016 than during the same period averaged between 2014-15 and 2016-17. The average temperature difference recorded at SLLP was 0.7°C greater.

The MRR data confirm the findings and inferences of previous studies (Bendix et al. 2006; Krois et al. 2013; Perry et al. 2014) that nocturnal precipitation is primarily stratiform. In our dataset, long duration stratiform events occurred primarily during DJF (Fig. 5; Table 3). The long durations during JJA 2016 in La Paz (Table 3) result from a small sample (n=9) containing exceptionally long events. As can be seen in two of the case studies (Figs. 8-9), the melting layer height during these storms is clearly evident and vertical velocity and reflectivity exhibit distinct horizontal layers, features that are commonly observed in vertical profiles of stratiform precipitation (Houze 1997; Yuter et al. 2006).

The mechanism responsible for producing stratiform precipitation, which remained unrecognized in the tropical Andes until radar-based studies were performed, is still under investigation. Areas such as eastern-facing slopes in the central Andes are exposed to enough moisture to allow precipitation responsible for the afternoon peak to continue developing into the overnight hours, through mechanisms such as katabatic flow colliding with Amazonian moisture, and produce the nighttime peak (Bendix et al. 2009; Mohr et al. 2014). Some studies have suggested that nighttime precipitation in the region originates in the Amazon basin from mesoscale convective systems (MCSs) (Bendix et al. 2006, 2009; Romatschke and Houze 2010). This is supported by the backwards air trajectories for the two stratiform case studies (Figs. 8c, 9c) which originate in the Amazon basin three days prior. These lowland MCSs form in response to daytime heating or by the convergence of katabatic flow, which develops from rapidly cooling high terrain after sunset, with unstable air in the Amazon (Bendix et al. 2009; Romatschke and Houze 2010). In one explanation, these regions of organized precipitation then proceed to propagate westward across the study area in the overnight hours (Bendix et al. 2006, 2009; Krois et al. 2013). However, strong mid-level northerly to southeastward flow along the eastern edge of the Andes may direct most convection that forms along the Andean foothills to the south and east before development into a large MCS occurs (Romatschke and Houze 2013). A different theory suggests that the stratiform region initiates precipitation via a seeder-feeder mechanism (Perry et al. 2014). This may allow for locally generated afternoon convection in the tropical Andes to organize and persist into the night.

Many of the heavy nighttime events in our dataset, defined as storms with total accumulated precipitation in the top quartile, exhibited convective precipitation at the onset before stratiform precipitation develops. This behavior, also observed in precipitation events in southern Ecuador (Bendix et al. 2006), was demonstrated by the event in Cusco on 8 October 2014 (Fig. 8) and may explain why melting layer heights lower during the period after the longest duration events begin (Table 2, 5). The melting layer height was observed to lower an average of 145 m in Cusco and 111 m in La Paz from the beginning to the end of the precipitation, an example of which can be seen also in Fig. 8. This may in part be explained by cooling associated with the evaporation of precipitation or in response to a loss of insolation.

Rain falling on the surface of a glacier reduces albedo, transfers heat that melts the surface, and eliminates the potential of the event to contribute snow depth to the annual layer (Francou et al. 2003; Salzmann et al. 2013). Although the altitude of the Quelccaya summit lies well above any melting layer height detected in Cusco, a present weather sensor located there suggests that liquid precipitation may occur at times even at that altitude (Perry et al. 2017). Strong El Niño periods, such as the event in 2015-16, are particularly detrimental to glacier health as positive temperature anomalies elevate the ELA and the wet season is delayed (Rabatel et al. 2013). These impacts may be varied however, as shown by positive precipitation anomalies during El Niño in the Cordillera Vilcanota in southern Peru (Perry et al. 2014). Even so, substantial ablation and exceptionally high ELAs observed on glaciers throughout our two study areas in July 2016 during fieldwork by our research team suggests the entire region is susceptible to impacts.

The strong El Niño in progress during the collection of the La Paz 2015-16 dataset may be responsible for the more elevated melting layer heights and higher variability when compared to Cusco 2014-15 or La Paz 2016-17 (Fig. 6; Table 6). Melting layer height values were at or above 5000 m for 47% of the values during SON-DJF 2015-16 alone. A series of events in La Paz in late February 2016 (one shown in Fig. 9) exhibited exceptionally high melting layer heights with a median value of 5165 m, likely due in part to anomalously elevated temperatures at the surface. The higher overall frequency of afternoon precipitation in La Paz, which was likely convective in nature and influenced by the El Niño conditions, may also have contributed to the differences in melting layer height distributions.

These observations of high melting layer heights is important because it is consistent with the reported rise in ELA and corresponding glacier retreat (Rabatel et al. 2013; Salzmann et al. 2013). Assuming regional coherency of the melting layer height during long duration stratiform events, melting layer heights above 5000 m implies that on occasion rain may occur high in alpine zones such as on the Nevado Chacaltaya (Perry et al. 2017) where a glacier existed until 2010 (Rabatel et al. 2013), and other glacierized regions in the tropical Andes. Although the altitude of the Quelccaya summit lies well above any melting layer height detected in Cusco, a present weather sensor located there (5,640 m) suggests that liquid precipitation may occur at times even at that elevation (Perry et al. 2017).

A fundamental limitation of our dataset is the sequential, rather than synchronous collection periods of the Cusco and La Paz MRR data. This makes it difficult to ascertain whether the observed differences in precipitation patterns are more a result of geography or atmospheric circulation. Either altered atmospheric patterns due to a strong El Niño or mass elevation effect and placement with respect to the Amazon rain forest could have resulted in the higher melting layer heights and less frequent nighttime stratiform events in La Paz. Regardless, these identified characteristics of precipitation in La Paz promote elevated ELAs on glaciers in the region and lead to less glacier mass at lower altitudes. In a warming climate, further increases in the height of the melting layer height and decreases in the frequency of frozen precipitation reaching the glacier surface will result in continued glacier retreat in the central Andes.

6. Conclusions

In this study, vertically pointing MRR data were utilized to form a more complete understanding of precipitation patterns in the tropical Andes. The timing, frequency, and melting layer height of precipitation events were analyzed, along with the conditions during heavy nighttime stratiform events and the direction trajectories from which moisture originated. Melting layer heights up to 5300 m were derived from the MRR datasets from La Paz and Cusco. This is almost as high as the uppermost ELAs (5400 m) during exceptionally negative mass balance years on glaciers studied in Rabatel et al. (2013). During 2015-16, which coincided with a strong El Niño event, melting layer heights were at or above 5000 m for 47% of the time in La Paz. Melting layer heights at these altitudes have important implications on the health of glaciers in the study area. Future research should consider how these melting layer heights detected over La Paz and Cusco relate to melting layer height values over higher terrain more broadly across the highland region.

A bimodal pattern in precipitation timing is evident at both La Paz and Cusco, with peaks in precipitation frequency in the afternoon and just before midnight. The afternoon peak was associated almost exclusively with convective storms, while the nighttime peak was dominated by stratiform precipitation. This was revealed by the character of the precipitation structure, including high melting layer heights and short event duration in the afternoon, and low melting layer heights and long event duration in the overnight hours. Long duration nighttime stratiform events primarily occurred during the DJF seasons. The-72 hr backwards air trajectories from three case studies show moisture advection from the Amazon basin. Although daytime heating in the presence of sufficient surface moisture drove the convective precipitation, the cause of the stratiform precipitation is uncertain. Further research will be needed in order to disentangle the relationships between the initiation of convection, its development into organized precipitation, and the direct and indirect influences that these systems have on the tropical Andes.

The MRR data also showed differences in the precipitation patterns between La Paz and Cusco. For example, the afternoon precipitation maximum was higher and occurred earlier in La Paz than in Cusco. Additionally, derived melting layer height values in La Paz and Cusco show differences both in spread and magnitude, with higher values and variability in La Paz, particularly during the 2015-16 year. These differences may result from either a product of geography (La Paz is at a higher altitude, surrounded by large mountains, and closer to the Amazon rainforest), ENSO phase (La Paz dataset was collected during a strong El Niño), or a combination of both. Simultaneous MRR observations in both La Paz and Cusco would help to uncover the differences between the impact of geography and atmospheric patterns on precipitation behavior in the area.

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References

Austin, P. M., and A. C. Bernis, 1950: A quantitative study of the "bright band" in radar precipitation echoes. *J. Meteorol.*, **7**, 145–151, doi:10.1175/1520-0469(1950)007<0145:AQSOTB>2.0.CO;2.

Bendix, J., R. Rollenbeck, and C. Reudenbach, 2006: Diurnal patterns of rainfall in a tropical Andean valley of southern Ecuador as seen by a vertically pointing K-band Doppler radar. *Int. J. Climatol.*, **26**, 829–846, doi:10.1002/joc.1267.

Bendix, J., K. Trachte, J. Cermak, R. Rollenbeck, and T. Naub, 2009: Formation of convective clouds at the foothills of the tropical eastern Andes (South Ecuador). *J. Appl. Meteorol. Climatol.*, **48**, 1682–1695, doi:10.1175/2009JAMC2078.1.

Cha, J.-W., S. S. Yum, K.-H. Chang, and S. N. Oh, 2007: Estimation of the Melting Layer from a Micro Rain Radar (MRR) data at the Cloud Physics Observation System (CPOS) site at Daegwallyeong Weather Station. *J. Korean Meteorol. Soc.*, **43**, 77–85.

Das, S., and A. Maitra, 2011: Some melting layer characteristics at two tropical locations in Indian region. *2011 30th URSI Gen. Assem. Sci. Symp. URSIGASS 2011*, 2–5, doi:10.1109/URSIGASS.2011.6050805.

Dee, D. P., and Coauthors, 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Q. J. R. Meteorol. Soc.*, **137**, 553–597, doi:10.1002/qj.828.

Falvey, M., and R. D. Garreaud, 2005: Moisture variability over the South American Altiplano during the South American low level jet experiment (SALLJEX) observing season. *J. Geophys. Res. Atmos.*, **110**, 1–12, doi:10.1029/2005JD006152.

Flenley, J. R., 1995: Cloud Forest, the Massenerhebung Effect, and Ultraviolet Insolation. *Tropical Montane Cloud Forests*, L.S. Hamilton, J.O. Juvik, and F.N. Scatena, Eds., Springer-Verlag New York, 150–155 http://link.springer.com/10.1007/978-1-4612-2500-3_9.

Francou, B., M. Vuille, P. Wagnon, J. Mendoza, and J.-E. Sicart, 2003: Tropical climate change recorded by a glacier in the central Andes during the last decades of the twentieth century: Chacaltaya, Bolivia, 16°S. *J. Geophys. Res.*, **108**, 4154, doi:10.1029/2002JD002959. http://doi.wiley.com/10.1029/2002JD002959.

Garreaud, R., 1999: Multiscale Analysis of the Summertime Precipitation over the Central Andes. *Mon. Weather Rev.*, **127**, 901–921, doi:10.1175/1520-0493(1999)127<0901:MAOTSP>2.0.CO;2.

——, 2000: Intraseasonal Variability of Moisture and Rainfall over the South American Altiplano. *Mon. Weather Rev.*, **128**, 3337–3346, doi:10.1175/1520-0493(2000)128<3337:IVOMAR>2.0.CO;2.

Garreaud, R., M. Vuille, and A. C. Clement, 2003: The climate of the Altiplano: Observed current conditions and mechanisms of past changes. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **194**, 5–22, doi:10.1016/S0031-0182(03)00269-4.

Hanshaw, M. N., and B. Bookhagen, 2014: Glacial areas, lake areas, and snow lines from 1975 to 2012: status of the Cordillera Vilcanota, including the Quelccaya Ice Cap, northern central Andes, Peru. *Cryosph.*, **8**, 359–376, doi:10.5194/tc-8-359-2014. http://www.the-cryosphere.net/8/1/2014/.

Houze, R. A., 1997: Stratiform Precipitation in Regions of Convection: A Meteorological Paradox? *Bull. Am. Meteorol. Soc.*, **78**, 2179–2196, doi:10.1175/1520-0477(1997)078<2179:SPIROC>2.0.CO;2. http://journals.ametsoc.org/doi/abs/10.1175/1520-0477(1997)078%3C2179:SPIROC%3E2.0.CO;2.

Hurley, J. V., M. Vuille, D. R. Hardy, S. J. Burns, and L. G. Thompson, 2015: Cold air incursions, δ 18 O variability, and monsoon dynamics associated with snow days at Quelccaya Ice Cap, Peru. *J. Geophys. Res. Atmos.*, **120**, 7467–7487, doi:10.1002/2015JD023323. http://doi.wiley.com/10.1002/2015JD023323.

Kellerhals, T., S. Brütsch, M. Sigl, S. Knüsel, H. W. Gäggeler, and M. Schwikowski, 2010: Ammonium concentration in ice cores: A new proxy for regional temperature reconstruction? *J. Geophys. Res. Atmos.*, **115**, 1–8, doi:10.1029/2009JD012603.

Krois, J., A. Schulte, E. P. Vigo, and C. C. Moreno, 2013: Temporal and spatial characteristics of rainfall patterns in the Northern Sierra of Peru – A case study for La Niña to El Niño transitions from 2005 to 2010. **48**, 23–48.

Kummerow, C., W. Barnes, T. Kozu, J. Shiue, and J. Simpson, 1998: The tropical rainfall measuring mission(TRMM) sensor package. *J. Atmos. Ocean. Technol.*, **15**, 809–817, doi:10.1175/1520-0426(1998)015<0809:TTRMMT>2.0.CO;2. papers2://publication/uuid/E7A45888-BEAF-4EB8-BF90-8195C40EB935.

L'hôte, Y., P. Chevallier, A. Coudrain, Y. Lejeune, and P. Etchevers, 2005: Relationship between precipitation phase and air temperature: comparison between the Bolivian Andes and the Swiss Alps. *Hydrol. Sci. J.*, **50**, 988–997, doi:10.1623/hysj.2005.50.6.989. http://www.tandfonline.com/doi/abs/10.1623/hysj.2005.50.6.989.

Lenters, J. D., and K. H. Cook, 1999: Summertime Precipitation Variability over South America: Role of the Large-Scale Circulation. *Mon. Weather Rev.*, **127**, 409–431, doi:10.1175/1520-0493(1999)127<0409:SPVOSA>2.0.CO;2.

Lundquist, J. D., P. J. Neiman, B. Martner, A. B. White, D. J. Gottas, and F. M. Ralph, 2008: Rain versus Snow in the Sierra Nevada, California: Comparing Doppler Profiling Radar and

Surface Observations of Melting Level. *J. Hydrometeorol.*, **9**, 194–211, doi:10.1175/2007JHM853.1.

Maahn, M., and P. Kollias, 2012: Improved Micro Rain Radar snow measurements using Doppler spectra post-processing. *Atmos. Meas. Tech.*, **5**, 2661–2673, doi:10.5194/amt-5-2661-2012.

Minder, J. R., and D. E. Kingsmill, 2012: Mesoscale Variations of the Atmospheric Snow Line over the Northern Sierra Nevada: Multiyear Statistics, Case Study, and Mechanisms. *J. Atmos. Sci.*, **70**, 916–938, doi:10.1175/JAS-D-12-0194.1. http://dx.doi.org/10.1175/JAS-D-12-0194.1.

Minder, J. R., T. W. Letcher, L. S. Campbell, P. G. Veals, and W. J. Steenburgh, 2015: The evolution of lake-effect convection during landfall and orographic uplift as observed by profiling radars. *Mon. Weather Rev.*, **143**, 4422–4442, doi:10.1175/MWR-D-15-0117.1.

Mohr, K. I., D. Slayback, and K. Yager, 2014: Characteristics of precipitation features and annual rainfall during the TRMM era in the central Andes. *J. Clim.*, **27**, 3982–4001, doi:10.1175/JCLI-D-13-00592.1.

Perry, L. B., A. Seimon, and G. M. Kelly, 2014: Precipitation delivery in the tropical high Andes of southern Peru: New findings and paleoclimatic implications. *Int. J. Climatol.*, **34**, 197–215, doi:10.1002/joc.3679.

Perry, L. B., and Coauthors, 2017: Characteristics of Precipitating Storms in Glacierized Tropical Andean Cordilleras of Peru and Bolivia. *Ann. Am. Assoc. Geogr.*, **4452**, 1–14, doi:10.1080/24694452.2016.1260439. https://www.tandfonline.com/doi/full/10.1080/24694452.2016.1260439.

Peters, G., B. Fischer, and T. Andersson, 2002: Rain observations with a vertically looking Micro Rain Radar (MRR). *Boreal Environ. Res.*, **7**, 353–362.

Rabatel, A., and Coauthors, 2013: Current state of glaciers in the tropical Andes: A multi-century perspective on glacier evolution and climate change. *Cryosphere*, **7**, 81–102, doi:10.5194/tc-7-81-2013.

Romatschke, U., and R. A. Houze, 2010: Extreme summer convection in South America. *J. Clim.*, **23**, 3761–3791, doi:10.1175/2010JCLI3465.1.

——, and R. A. Houze, 2013: Characteristics of Precipitating Convective Systems Accounting for the Summer Rainfall of Tropical and Subtropical South America. *J. Hydrometeorol.*, 120927133830006, doi:10.1175/JHM-D-12-060.1.

Salzmann, N., C. Huggel, M. Rohrer, W. Silverio, B. G. Mark, P. Burns, and C. Portocarrero, 2013: Glacier changes and climate trends derived from multiple sources in the data scarce Cordillera Vilcanota region, southern Peruvian Andes. *Cryosphere*, **7**, 103–118, doi:10.5194/tc-7-103-2013.

Tokay, A., D. A. Short, C. R. Williams, W. L. Ecklund, and K. S. Gage, 1999: Tropical Rainfall Associated with Convective and Stratiform Clouds: Intercomparison of Disdrometer and Profiler Measurements. *J. Appl. Meteorol.*, **38**, 302–320, doi:10.1175/1520-0450(1999)038<0302:TRAWCA>2.0.CO;2. http://journals.ametsoc.org/doi/abs/10.1175/1520-0450%281999%29038%3C0302%3ATRAWCA%3E2.0.CO%3B2.

Vimeux, F., P. Ginot, M. Schwikowski, M. Vuille, G. Hoffmann, L. G. Thompson, and U. Schotterer, 2008: Climate variability during the last 1000 years inferred from Andean ice cores: A review of methodology and recent results. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **281**, 229–241, doi:10.1016/j.palaeo.2008.03.054. http://dx.doi.org/10.1016/j.palaeo.2008.03.054.

Vuille, M., 1999: Atmospheric Circulation Over the Bolivian Altiplano During Dry and Wet Periods and Extreme Phases of the Southern Oscillation. **1600**, 1579–1600.

Vuille, M., and C. Ammann, 1997: Regional snowfall patterns in the high, arid Andes. *Clim. Change*, **36**, 413–423, doi:10.1007/978-94-015-8905-5_10. http://link.springer.com/chapter/10.1007/978-94-015-8905-5_10.

Wagnon, P., P. Ribstein, B. Francou, and J. E. Sicart, 2001: Anomalous heat and mass budget of Glaciar Zongo, Bolivia, during the 1997/98 El Nino year. *J. Glaciol.*, **47**, 21–28, doi:10.3189/172756501781832593.

White, A. B., D. J. Gottas, E. T. Strem, F. M. Ralph, and P. J. Neiman, 2002: An automated brightband height detection algorithm for use with Doppler radar spectral moments. *J. Atmos. Ocean. Technol.*, **19**, 687–697, doi:10.1175/1520-0426(2002)019<0687:AABHDA>2.0.CO;2.

Wolter, K., and M. S. Timlin, 1993: Monitoring ENSO in COADS with a seasonally adjusted principal component index. *Proc. 17th Clim. Diagnostics Work.*, 52–57.

Yuter, S. E., D. E. Kingsmill, L. B. Nance, and M. L??ffler-Mang, 2006: Observations of precipitation size and fall speed characteristics within coexisting rain and wet snow. *J. Appl. Meteorol. Climatol.*, **45**, 1450–1464, doi:10.1175/JAM2406.1.

Table 1. Summary of data sources.

Source and Location	Variable(s)	Temporal Scale	Period	Elevation (m asl)
Micro Rain Radar/ Cusco, Peru	radar reflectivity, echo top height, melting layer height	1 minute	2014-2015	3350
Micro Rain Radar/ La Paz, Bolivia	radar reflectivity, echo top height, melting layer height	1 minute	2015-2016	3440
SPZO Metars/ Cusco, Peru	temperature, precipitation	1 hour	2014-2015	3248
SLLP Metars/ El Alto, Bolivia	temperature, precipitation	1 hour	2015-2016	4062
Met Station/ Cota Cota, La Paz, Bolivia	temperature, precipitation	1 hour	2015-2016	3440
Rawinsonde/ Cota Cota, La Paz, Bolivia	temperature	---	2016, 2017	---
ERA-Interim/ ECMWF	atmospheric reanalysis	6 hour	2014-2016	---
GDAS 0.5°/ NOAA	backward air trajectories	1 hour	2014-2015	---

Table 2. Diurnal statistics for the duration of precipitation events that began during 13-18, 19-00, 01-06, and 07-12 UTC in La Paz and Cusco.

Location	Period	Period (UTC)	Median Event Duration (hr)	Median Top Quartile Event Duration (hr)
Cusco	midday	13-18	3.1	7.6
	afternoon	19-00	2.2	9.4
	overnight	01-06	1.3	5.0
	early morning	07-12	0.7	4.0
La Paz	midday	13-18	2.0	5.1
	afternoon	19-00	1.2	5.9
	overnight	01-06	2.1	8.0
	early morning	07-12	1.6	4.7

Table 3. Seasonal durations for precipitation events during DJF, MAM, JJA, and SON in La Paz and Cusco.

Location	Period	Median Event Duration (hr)	Median Top Quartile Event Duration (hr)
Cusco	SON 2014	0.9	4.1
	DJF 2014-15	3.3	8.8
La Paz	SON 2015	1.6	6.3
	DJF 2015-16	1.8	6.6
	MAM 2016	1.2	4.1
	JJA 2016	2.9	6.7
	SON 2016	1.3	3.7
	DJF 2016-17	2.0	6.7

Table 4. Summary of computed melting layer height statistics from all events, and from heavy (top quartile of observed precipitation totals) stratiform events, 18 events in Cusco, Peru and 27 in La Paz, Bolivia.

	All Events (MLH m asl)		**Heavy Events (MLH m asl)**	
	Cusco	**La Paz**	**Cusco**	**La Paz**
Maximum	5300	5363	5300	5310
Minimum	4238	4065	4304	4065
Mean	4820	4873	4808	4883
Median	4839	4884	4822	4907
Standard Deviation	187	231	196	254

Table 5. Diurnal MLH statistics for 13-18, 19-00, 01-06, and 07-12 UTC in La Paz and Cusco.

Location	**Period**	**Period (UTC)**	**Median MLH (m asl)**	**Standard Deviation (m asl)**
Cusco	midday	13-18	4859	189
	afternoon	19-00	4925	170
	overnight	01-06	4809	179
	early morning	07-12	4745	169
La Paz	midday	13-18	4919	192
	afternoon	19-00	4940	229
	overnight	01-06	4833	255
	early morning	07-12	4841	219

Table 6. Seasonal MLH statistics for DJF, MAM, JJA, and SON in La Paz and Cusco.

Location	Period	Median MLH (m asl)	Standard Deviation (m asl)
Cusco	SON 2014	4738	175
	DJF 2014-15	4850	185
La Paz	SON 2015	4790	179
	DJF 2015-16	5064	200
	MAM 2016	4903	189
	JJA 2016	4401	185
	SON 2016	4703	191
	DJF 2016-17	4890	145

Table 7. Meteorological and MRR statistics for the case studies. Meteorological vales were obtained from SPZO and a station collocated with the La Paz MRR. Duration values are calculated using 3 hour breaks, and therefore represent parts of the event that may exist outside of the range of the MRR image.

Event Date	Total Precipitation (mm)	Average Temp (°C)	Total Duration (hr)	Median MLH (m asl)
Cusco, 15 Jan 15	0.8	16.8	3.3	---
Cusco, 08 Oct 14	16.6	9.4	5.8	4681
La Paz, 25 Feb 16	24.2	12.1	42.2	5129

Table 8. ERA-Interim variables for the grid cell closest to the MRR at the event location and at the reanalysis hour closest to the middle of each event.

	Wind Speed (ms^{-1})		Wind Direction (°)		Geopotential height (m asl)	
Event Date	**500 mb**	**250 mb**	**500 mb**	**250 mb**	**500 mb**	**250 mb**
Cusco, 15 Jan 15	4.8	8.0	207	343	5890	10971
Cusco, 08 Oct 14	5.9	8.0	125	242	5883	10979
La Paz, 25 Feb 16	6.8	2.0	218	227	5887	11049

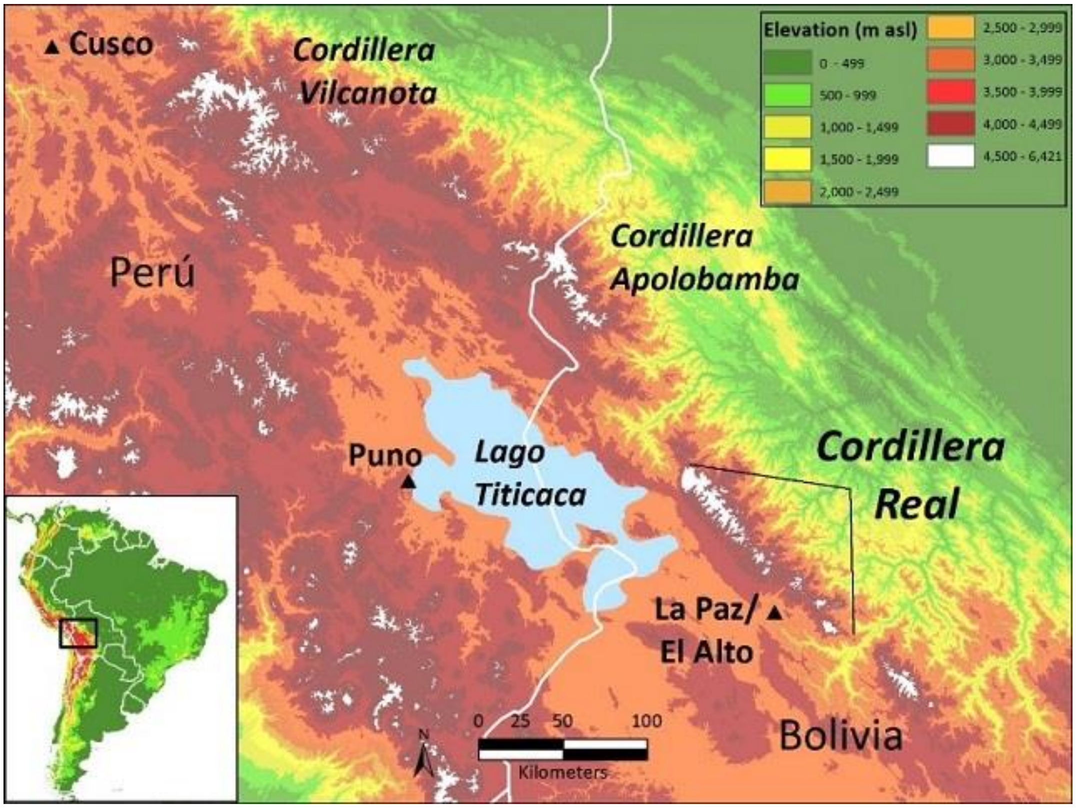

Fig. 1. Study area showing Cusco, Peru and La Paz, Bolivia (locations of the MRR) and surrounding cordilleras.

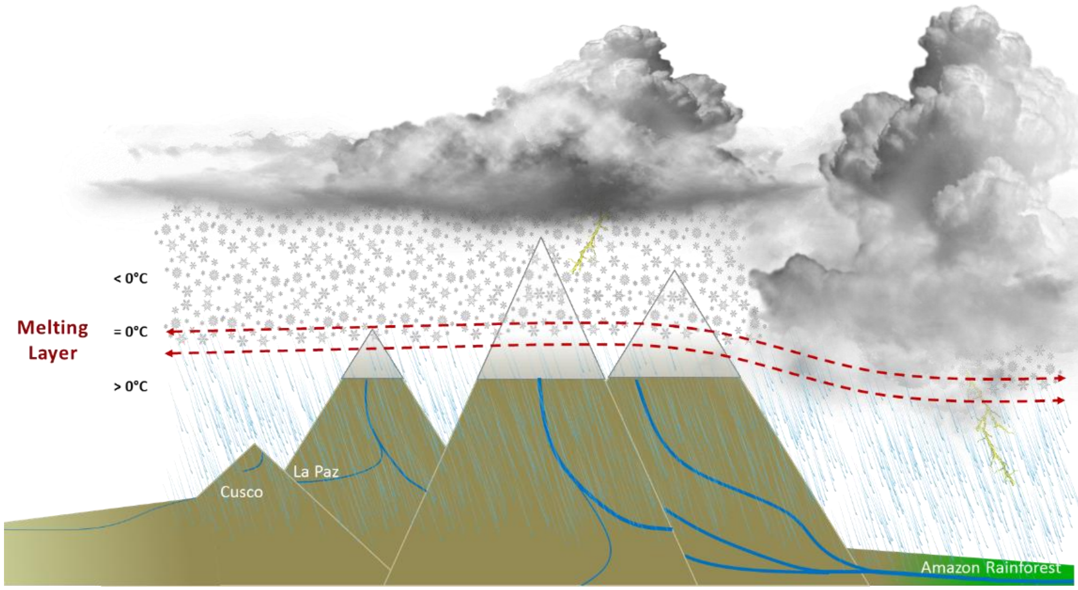

Fig. 2 Representation of the importance of the melting layer height in the study area.

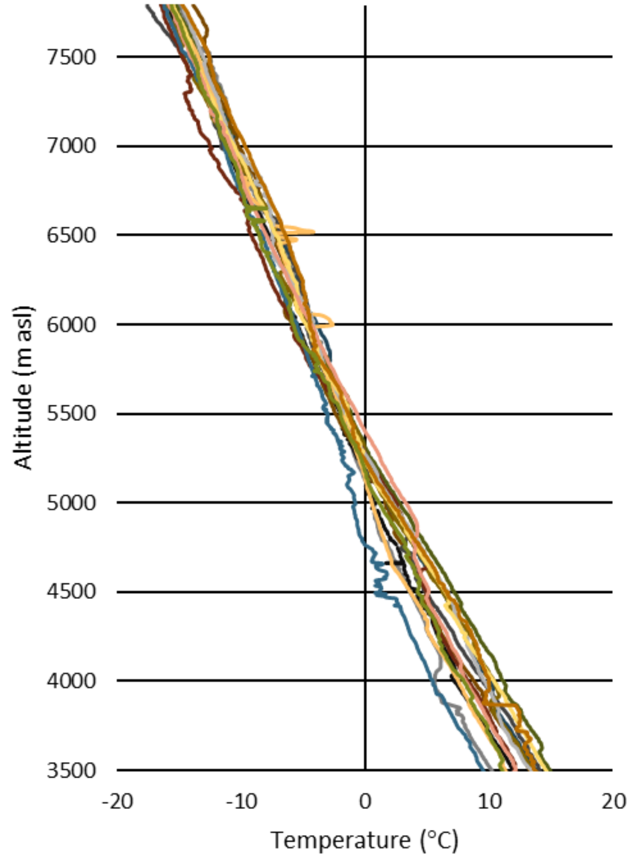

Fig. 3 Vertical temperature profiles during precipitation events recorded by 5 rawinsonde launches in Mar 2016 and 10 in Jan 2017 at the site of the La Paz MRR.

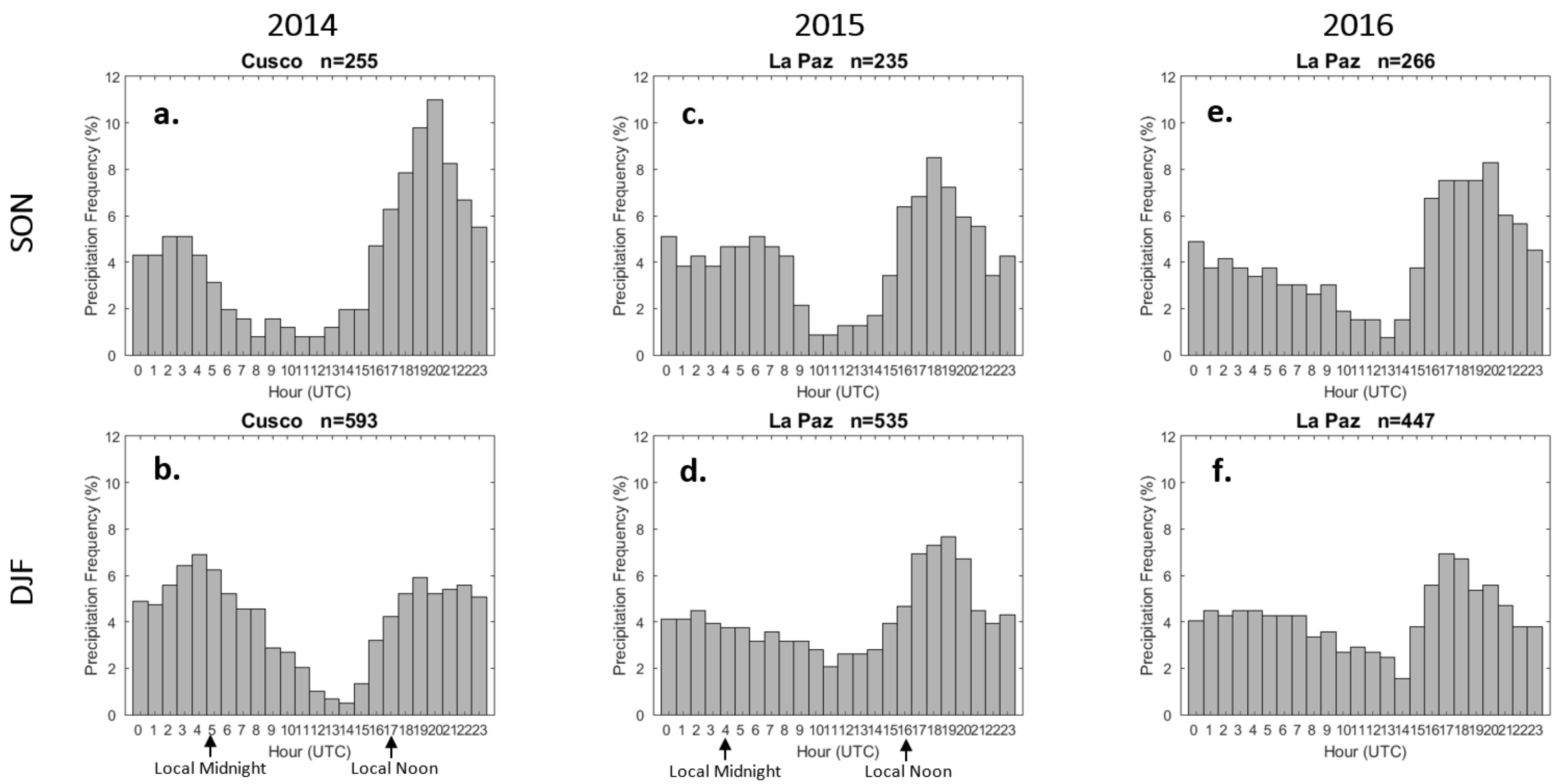

Fig. 4 Hourly frequency of precipitation detected by the MRR in a-b) Cusco, Peru (Sep 2014-Feb 2015, 107 events) and c-f) La Paz, Bolivia (Oct 2015-Feb 2016, 103 events; Sep 2016-Feb 2017, 104 events). N = the number of hours in each histogram.

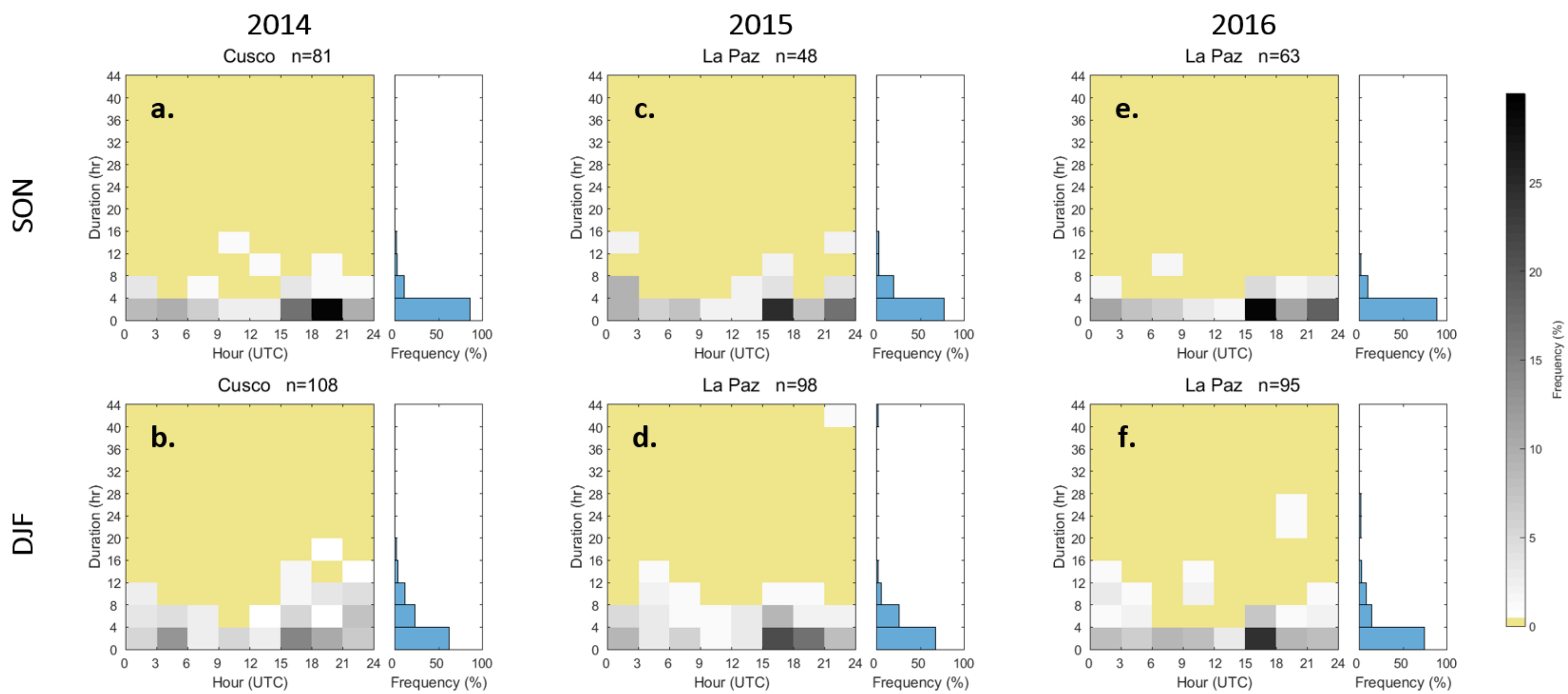

Fig. 5 Scatter density plots showing the diurnal pattern of the hour in which storms with precipitation reaching the surface begin, and their duration, separated by season. Histograms show the distribution of the durations. A maximum of 3 hours with no surface precipitation is allowed before a new storm begins. N = the number of events in each plot.

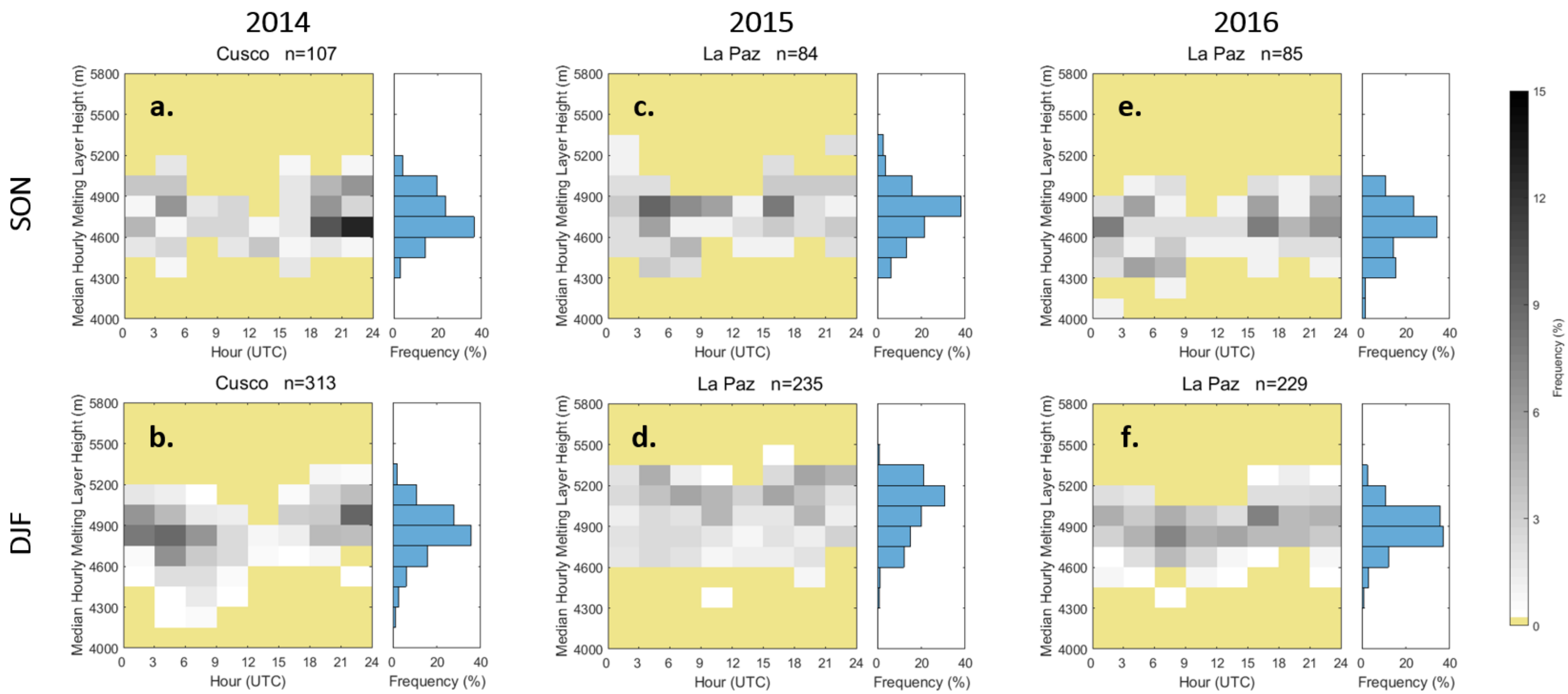

Fig. 6 Scatter density plots showing the diurnal pattern the median hourly melting layer height, separated by season. Histograms show the distribution of the median melting layer height values. N = the number of hours in each plot.

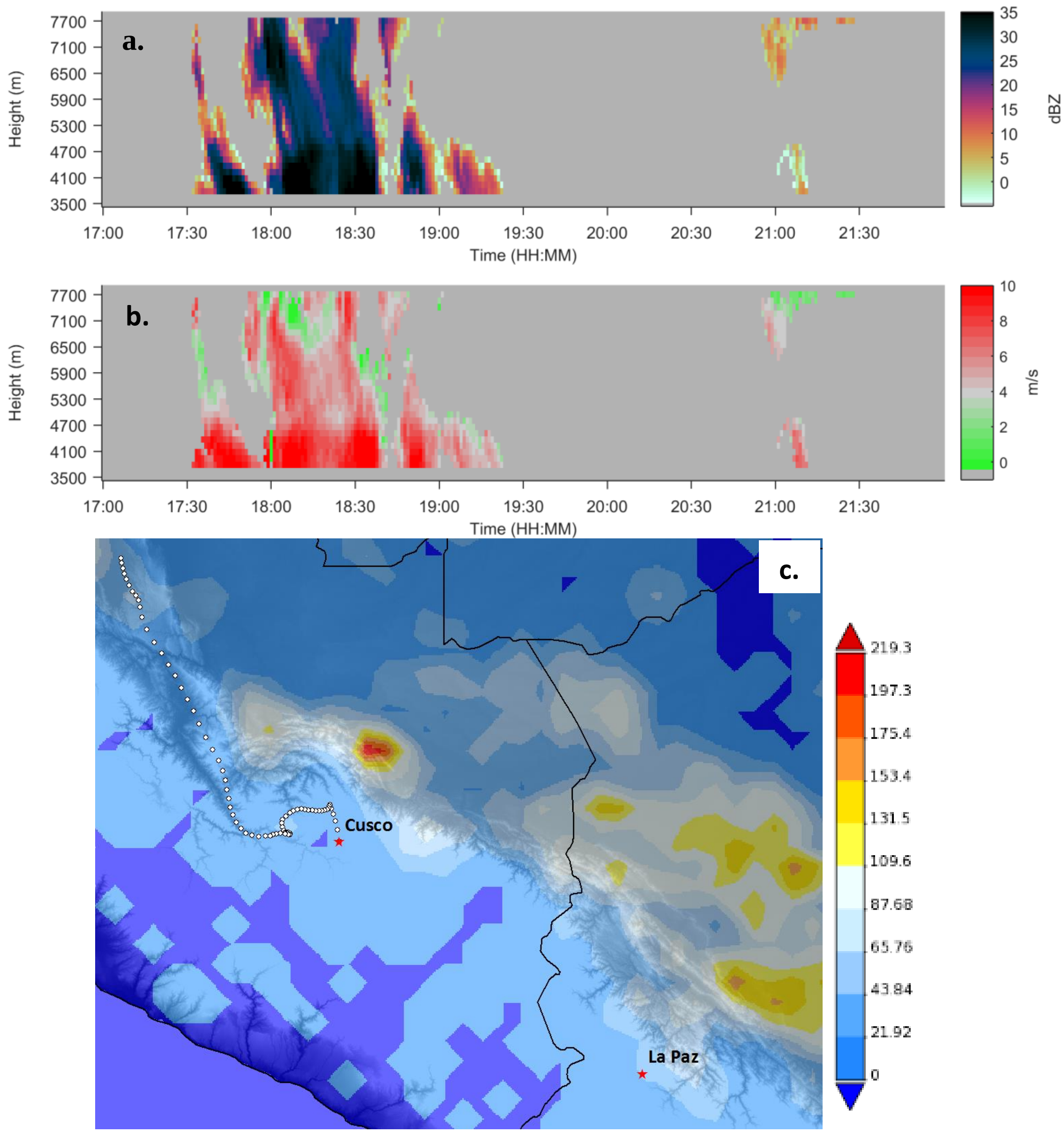

Fig. 7 a) Vertical time-height reflectivity and b) Doppler velocity profiles, and c) TRMM derived accumulated precipitation (1030-2230 UTC 15 Jan 2015; mm) and HYSPLIT derived 72-hr backwards air trajectory of a convective precipitation event over Cusco, Peru on 15 Jan 2015. In a) and b), white boxes and numbers indicate median hourly computed MLHs.

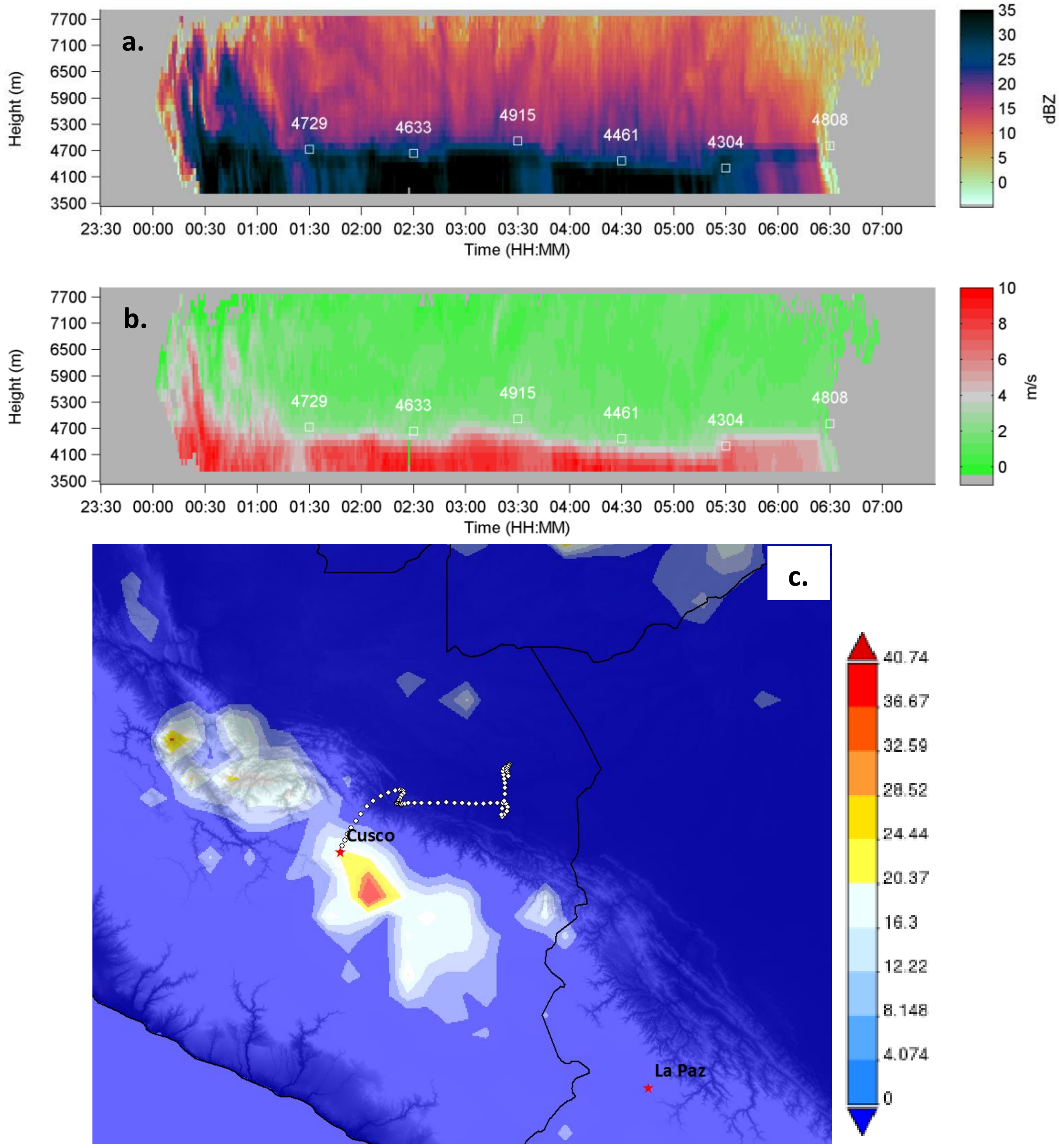

Fig. 8 As in Figure 7, but for a stratiform precipitation event over Cusco, Peru on 08 Oct 2014. (TRMM derived accumulated precipitation: 2230 UTC 07 Oct 2014-1030 UTC 08 Oct 2014)

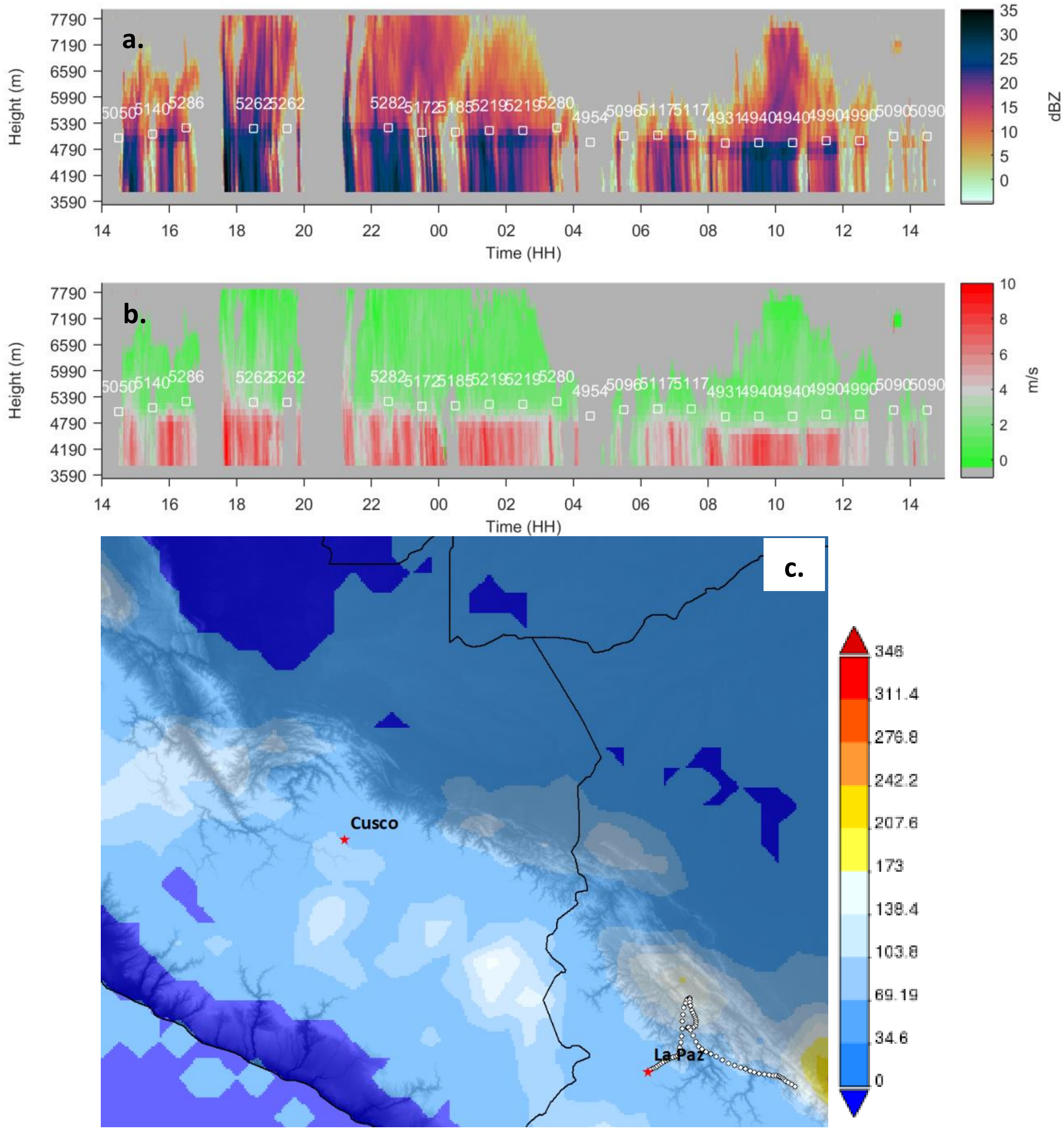

Fig. 9 As in Figure 7, but for a stratiform precipitation event over La Paz, Bolivia on 25 Feb 2016. (TRMM derived accumulated precipitation: 0430 UTC 25 Feb 2016-1930 UTC 26 Feb 2016)

Vita

Jason Lee Endries was born and grew up just south of Richmond, VA, in Chesterfield County. His parents, Mark and Bonnie Endries, raised him and his three younger brothers with an openness to let them follow their passions, which is what started Jason on the path to where he is today. After graduating from the Spanish Immersion program at Manchester High School in 2011 with a newfound appreciation for Latin American culture and the Spanish language, he continued to North Carolina State University (NCSU) in Raleigh, NC. There, he earned his B.S. in Meteorology and gained undergraduate research experience under the guidance of Dr. Sandra Yuter. In addition to academics, Jason created unforgettable memories and long-lasting friends at his time at NCSU. Before graduation in May 2015, he accepted a position as a graduate research assistant with Dr. Baker Perry at Appalachian State University. A perfect melding of his interests in Spanish and Latin America, meteorology, and observational research, Jason spent the next two years in this role and constructed this thesis piece by piece along the way.

Upon graduating with an M.A. in Geography in May 2017 and doing a bit of celebratory traveling over the summer, Jason plans to continue to study the weather, to be sustainable, and most importantly to pursue what makes him happy.